Numerical analysis of real-world cyclist crashes: impact speed, collision mechanism and movement trajectories

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Abstract

This paper describes the development and testing of a three-dimensional computer model of a bicycle and rider. The model was developed using MADYMO and will assist in the reconstruction of bicycle crashes. In particular the model will be used to determine the rider's pre-impact speed and kinematics during the impact. Three exemplar real-world bicycle crashes were reconstructed using a multi-body system (MBS) modelling technique. The models were set up in accordance with crash information obtained from at-scene investigations, and police and witness reports of exemplar collisions. The computer crash reconstructions gave reasonable representations of the real-world crashes. The modelling identified the influence of a number of input variables, eg. pre-crash speeds, and outputs, eg. cyclist trajectory. This study is a part of a major research project examining the performance of bicycle and motorcycle helmets. The computer simulations will assist in determining the head impact velocities in real world collisions.

Keywords

Crash reconstruction, bicycle, cyclist, impact velocity, simulation, collision, helmets

Introduction

Cycling is one of the most popular recreational and sporting activities in Australia [1]. It is also a method of commuting. Bicycle related crashes are of special interest because they often involve children and young adults, the injuries result in hospitalisation and there is a high degree of associated socioeconomic burden [2].

Whilst bicycle safety has been a significant concern for road safety authorities, cycling organisations, and riders, there has been little research conducted in Australia into the types of crashes experienced by riders, especially when compared with that for vehicles and other modes of transport. In particular, there is a lack of information describing bicycle crash dynamics and related injury mechanisms.

Physical evidence at the crash scene, vehicle damage, witness reports and injury descriptions are used to reconstruct crashes, including cyclist speed and trajectory. However, due to the complex kinematics involved in a bicycle collision, the evidence available is often insufficient for investigators to determine accurately the pre-impact velocities of the cyclist or any other vehicle, and the speeds of subsequent cyclist impacts.

The overall aim of this project is to develop a generic (unhelmeted) cyclist computer model in order to simulate any type of bicycle-related crash by simply changing the crash configuration, rider characteristics and the object struck. It is envisaged that the use of such a model can improve the understanding of impact injuries, pre-impact speed and kinematics of the rider during a real-world bicycle crash [3, 4]. Specifically, the model will be applied in an Australian Research Council (ARC) funded Linkage Project that is being conducted at The University of New South Wales (UNSW) into pedal and motor cycle helmet performance.

Methods

Crash reconstruction was performed using the Mathematical Dynamic Model (MADYMO) solver [5], which combines multi-body system (MBS) modelling and finite element analysis (FEA).

Multi-body ellipsoid segments were used to model the bicycle, as shown in Figure 1, which consists of five rigid bodies: the frame, front fork, two wheels and the seat. The geometrical dimensions of the bicycle model are based on those of a standard racing bicycle sold in Australia (mass = 13.6 kg and frame size = 55cm). The contact stiffness properties used for the bicycle model were based on laboratory test data obtained by the authors.

Reconstructions utilised the Hybrid III anthropometric dummy models developed by TNO [5].

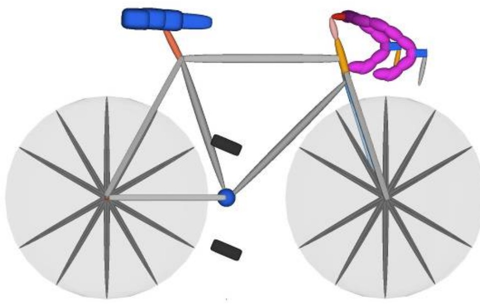

Figure 1**:** Bicycle Model

Crash information extracted from scene investigations and police reports of crashes were used to set up the simulation models. In order to start the reconstruction study, input data for accident reconstruction was needed. The input data included a short description of the anthropometry of the cyclist, geometry and mechanical characteristics of the surface struck, and the initial speeds of the opponent vehicle and cyclist. Each cyclist's speed at the time of impact was determined from two main sources: (i) the in-depth crash investigations, and (ii) the self-reported speed by the cyclists. Parametric variation of pre-impact speed was also investigated.

Reconstruction Cases

In terms of real data, three types of bicycle collision cases were selected for the present study. The data were provided in an unidentifiable form to researchers at UNSW. In these cases, the point of impact and injuries sustained by the cyclists were known.

Case 1 Impact with a guardrail
A bicycle rider lost control of his bicycle on a road and collided with a Armco guardrail to his left. The bicycle contacted the rail, and the rider was thrown forward impacting a steel C-section support post. The rider suffered severe brain injury with skull, rib and spinal fractures.

Case 2 Bicyclist-car impact
A rider was struck by a passenger car, travelling at approximately 75km/h, from his right as he turned right at a T-intersection (Figure 2). As a result of the impact, the rider suffered severe head injuries including skull fractures and brain damage, and various spinal injuries and fractures.

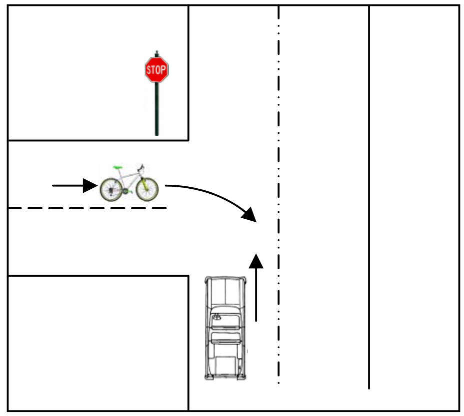

Figure 2: Schematic diagram of crash 2, not to scale.

Case 3 Bicycle-bicycle collision on bike track
Rider 1 entered an underpass along a dual lane bicycle path and collided with a bicyclist (Rider 2). Rider 2 was travelling in the opposite direction. Rider 1 then collided with the concrete wall of the underpass (Figure 3), suffering serious cervical spinal injuries as a result.

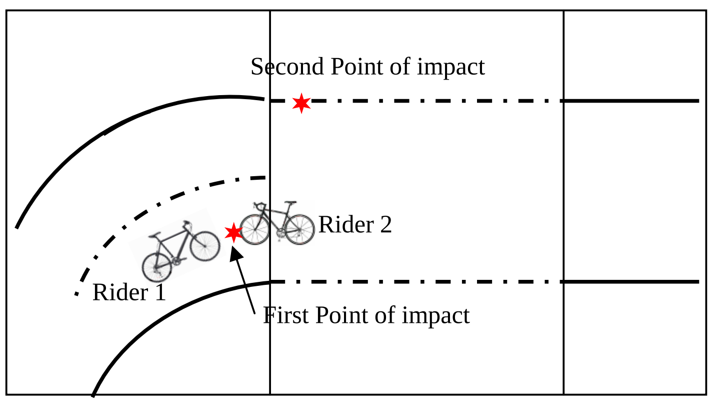

Figure 3: Schematic diagram of crash 3, not to scale.

Results

Case 1 Impact with a guardrail
Figure 4 shows a time-series of the MADYMO simulation of Case 1. A multi-body model of the 50th-percentile Hybrid III anthropometric dummy occupant has been used here to represent the rider. The model shows the front tyre striking the kerb and the bicycle handlebar scraping along the guardrail. The injuries sustained by the rider are consistent with the head and chest impacting the unguarded C-section post. After striking the post, the rider was rotated and thrown over the guardrail, hitting the ground.

The available evidence from the scene, witness and police report did not enable a clear determination of the rider's speed at the point of loss of control. However, based on a speed parametric study, the rider's speed at the point of loss of control was estimated in these analyses to be around 35km/h, and the kinematics of the rider obtained from the simulation is consistent with the injuries sustained (depressed fracture of the frontal skull and fractured ribs). According to Otte [6] skull and rib fractures can occur to cyclists during impacts as low as 20 km/h and on average at 40-60km/h. However, the study by Otte only considered body parts impacted by car structures. In the present study, the rider impacted a steel guardrail post, which is much stiffer than a vehicle body, therefore, head and rib fractures were more likely to occur at a lower impact speed around 35km/h.

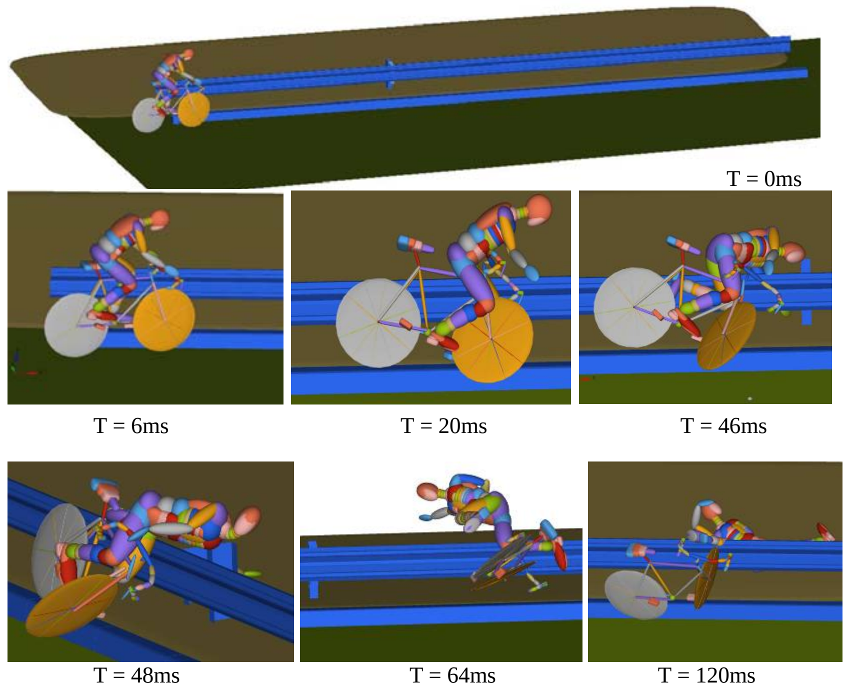

Figure 4: MADYMO simulation of a rider losing control after striking a concrete kerb, followed by a steel guardrail.

Case 2 Bicyclist-car impact
Figure 5 shows the MADYMO simulation of a cyclist travelling at 10km/h at the time of impact with a passenger car. A multi-body model of the 5th-percentile Hybrid III female dummy was used to represent the smaller rider. Contact interactions between the dummy and the vehicle were defined. The contact stiffness of the vehicle was based on the literature [4, 7]. The dents in the bonnet were observed to occur from the first contact with the cyclists' right leg. The cyclist then slid over the bonnet panel and his head struck the lower right portion of the windscreen.

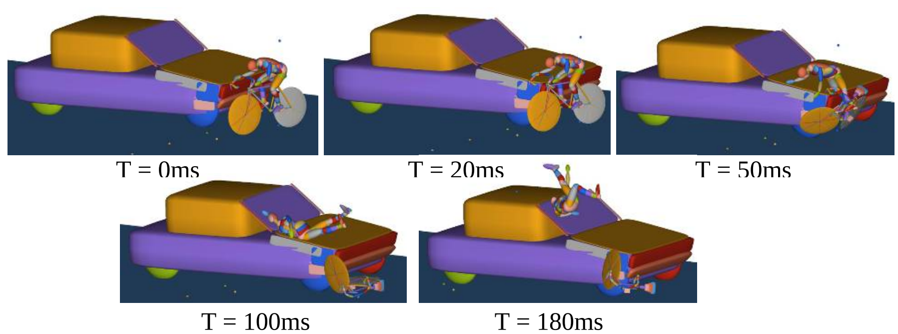

Figure 5: MADYMO simulation of a cyclist hit by a passenger car

The rider's velocity at impact was examined. When the cyclists' velocity at the time of impact was raised to 20km/h, the rider's head missed the windscreen completely (Figure 6). This analysis indicated that the likelihood of the rider's head impacting against the windscreen is dependent on the velocity of the rider at the time of the collision. The MADYMO model was very useful in clarifying the impact kinematics.

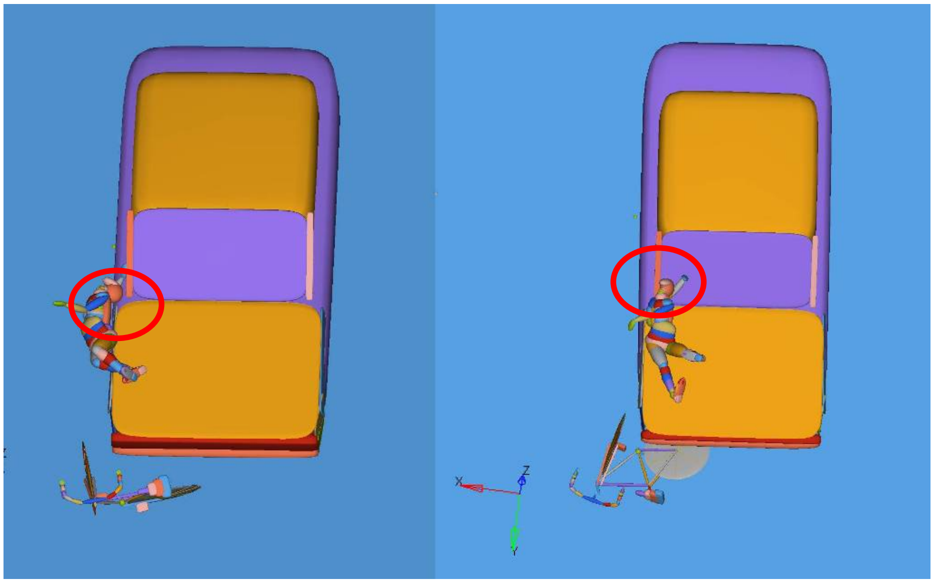

Figure 6: Simulated dummy kinematics at different impact speeds. At 20km/h the rider missed the windscreen (left), and at 10km/h the rider hit the lower left portion of the windscreen (right).

Case 3 Bicycle-Bicycle collision on bike track
Figure 7 shows a time-series of the MADYMO simulation of a cyclist-cyclist collision with an impact velocity of 25km/h. The cyclist travelling east along a bike path (Rider 1) had a head-on collision with a second cyclist who was travelling west (Rider 2). Rider 1 then collided with the concrete wall of an underpass.

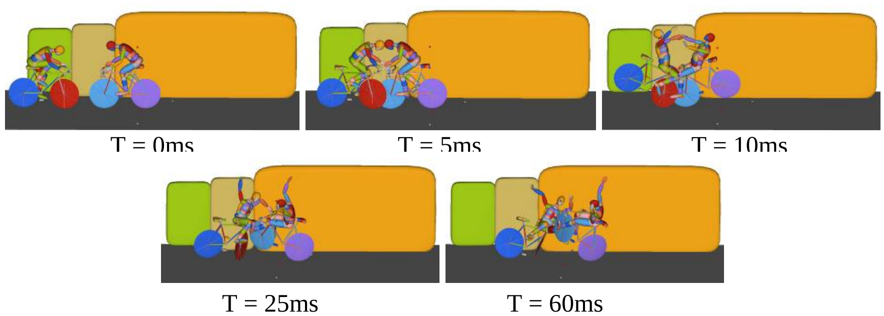

Figure 7: MADYMO simulation of two cyclists colliding with one another on a bicycle path just outside an underpass.

When the impact velocity between the two cyclists was varied, Rider 1 was found to impact the concrete wall at different points. For example with an impact velocity of 25km/h, Rider 1 collided with the concrete wall near the western entrance. When the impact velocity was raised to 30km/h, the resulting impact was further along the wall, near the middle section (Figure 8).

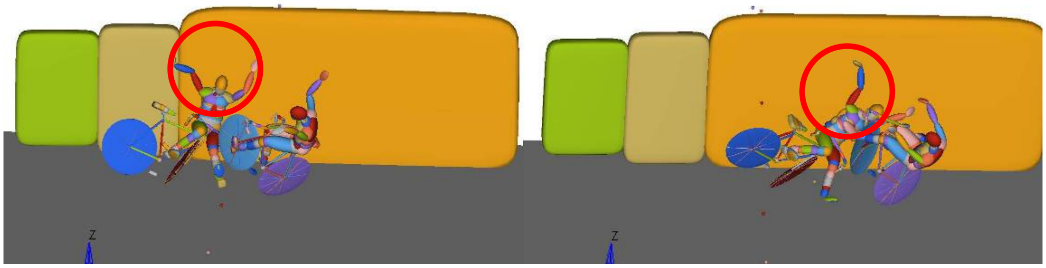

Figure 8: Simulated rider's kinematics at different impact speeds. At 25km/h, Rider 1 hit the concrete wall near the underpass entrance (left), and at 30km/h the rider hit the middle section of the concrete wall (right).

Discussion

In the present study, three types of real-world bicycle crashes were reconstructed using MADYMO software to better understand the kinematics of the crashes and confirm analyses based on traces at the scene, and police and witness reports.

From the simulation results, it can be seen that the bicycle-rider model can predict general collision and injury mechanisms of a cyclist. Simulation and parametric studies revealed that small variations in cyclist pre-impact speeds could greatly affect the resulting collision mechanics. By varying the speeds of each vehicle, a better fit could be obtained between the witness marks and the simulations.

These MADYMO simulations provide a means of determining rider kinematics and collision mechanics; however, computer simulation of bicycle rider behaviour during a collision event is a challenging task. This is because it is often difficult to determine the impact velocity of vehicle-bicycle, bicycle-bicycle or single bicycle collisions for accident reconstruction. For instance, new vehicles that are equipped with an antilock braking device (ABS) do not usually leave any braking marks for the investigator to determine the pre-impact speed for either the striking vehicle or the cyclist. Also the movement of the riders and their bicycle after the impact is complex, as is the contact interaction between rider and bicycle, bicycle and object struck, and rider and object struck. Nevertheless, the injury mechanisms, pre-impact speed and post-impact kinematics of cyclists as a result of different collisions have been successfully investigated using this MADYMO bicycle-rider model.

The model is efficient in predicting the damage chronology, trajectory of the cyclist, and collision mechanism. Further, the MADYMO modelling allows variations in rider speeds and enables the rider trajectory to be examined and correlated with the case information. It is envisaged that through thorough field investigation, a bicycle-rider model can be applied by researchers to better reconstruct bicycle collisions, and better understand the collision mechanics and injury mechanisms involved. Moreover, the MADYMO simulation allows an output of injury parameters, such as Head Injury Criterion (HIC), Neck Injury Predictor (N_{ij}), Tibia Index and among others, which improves the understanding of injury mechanism, injury severity and the situations in which they occur [5]. Another advantage of using MADYMO is that a scaled dummy model can be generated with appropriate inertial and geometric properties to represent a human subject based on their age, weight, height, gender and/or specific body dimensions. This will enable researchers to reconstruct and correlate injuries with real-life cases.

The NSW Roads & Traffic Authority (RTA) data show that on average over 80% of cyclist fatalities involved riders who were wearing a helmet, and of the injury cases over 60% of pedal cyclists were helmeted [8]. However, in these cases, the role of the helmet in protecting against head injury could not be ascertained. In the present model, the dummy rider model did not include a protective helmet of any kind. A finite element model of a generic bicycle helmet, therefore, should be incorporated into the dummy model in order to improve our understanding of injury mechanisms at the head and neck level, the role of current helmets, and ultimately to optimise the design of a protective helmet to better protect cyclists.

For this study, cyclists' travelling speed was determined from evidence found at the scene as well as the self-reported speed at the time of collision by the rider. However, the accuracy and validity of self-reported speed is difficult to ascertain. A study by Thompson et. al. [9] has indicated that teenagers and adults tend to overestimate their riding speed. Accurate determination of pre-crash speed is important as it serves as an input parameter for numerical simulation. Therefore, reliable and accurate riding speed estimates for the commuter and recreational populations of cyclists warrants further study.

Conclusion

Collision reconstructions using three-dimensional multi-body models allow researchers to relate impact speed, collision mechanics, impact regions, cyclist injuries and trajectories. It is envisaged that with further research and development, the MADYMO bicycle-rider model developed in this study can be widely used for bicycle accident reconstructions. The model provides insights into the crash dynamics and predicts cyclist kinematics. Results from the parametric study indicated that a cyclist's kinematics are significantly affected by the pre-impact travelling speed of the rider. The model will be applied to the study of helmet impacts and helmet performance.

Acknowledgments

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Disclaimer: The cases presented draw on some of the circumstances of real crashes. However the case modelling and any conclusions given in this paper are for research purposes only and in the context of the Pedal and Motor Cycle Helmet Performance Study. The authors specifically note that the analyses and findings are not intended to be nor are they directly valid or applicable to any specific collision.